

LITERATURE SURVEY AND FEASIBILITY STUDY OF
USE OF ELECTRON BEAM FLUORESCENCE FOR
TEMPERATURE MEASUREMENT IN CO₂

By Dr. Jacob Becher
Dr. George S. Ofelt



Prepared under Contract No. NAS 1 - 9287 by
OLD DOMINION UNIVERSITY
RESEARCH FOUNDATION
NORFOLK, VIRGINIA 23508

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

(NASA-CR-112803) LITERATURE SURVEY
AND FEASIBILITY STUDY OF USE OF
ELECTRON BEAM FLUORESCENCE FOR
TEMPERATURE MEASUREMENT IN CO₂
(Old Dominion Univ.) 19 p

N94-71886

Unclas

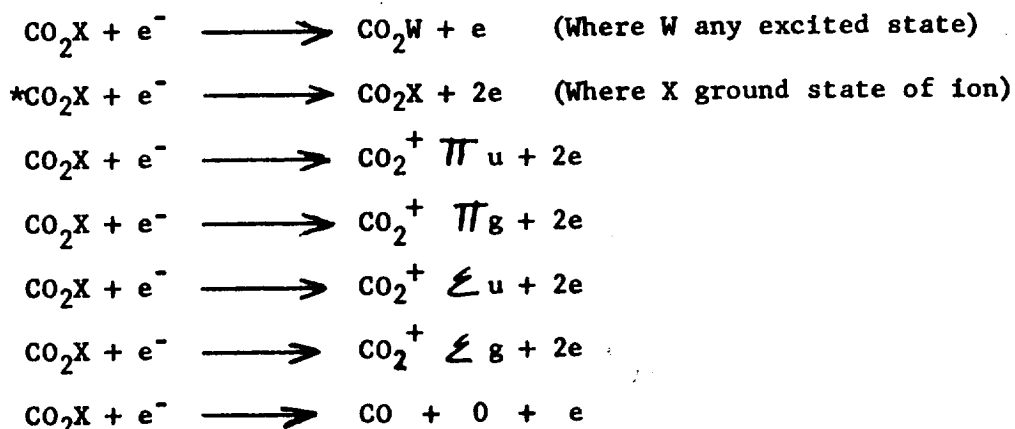
29/25 0008611

I. INTRODUCTION

A literature feasibility study was made to determine the possibility of measuring the temperature of CO_2 by observing the fluorescence produced by an incident high energy electron beam. This technique, using N_2 gas, is successfully used at NASA, Langley. The use of CO_2 would appear to have several basic advantages over the use of N_2 . The rotation levels are closer together and thus more levels will be populated, thus potentially improving the temperature measurement. Secondly, the fact that the first excited vibration level is only 600 cm^{-1} above ground would indicate that more sensitive measurements of vibration and rotational temperature could be measured in CO_2 .

To examine the applicability of CO_2 for this purpose, the following must be examined: (a) The energy distributed among the various electronic levels of the molecule or ion produced by the incident electron beam on the neutral molecules (whose energy levels are shown in Fig. I); (b) The Frank-Condon factors to determine which vibrational levels will be populated; (c) The transition probabilities from various excited electronic levels, and (d) The Frank-Condon factors for the fluorescent levels. It is also important to examine whether the various vibrations overlap to hinder identification and result in spurious intensity measurements. Should there be a band system which has favorable conditions, then we would need to know the necessary resolution for resolving the rotational lines.

The competing processes produced by an impinging electron beam can be divided into the following categories:

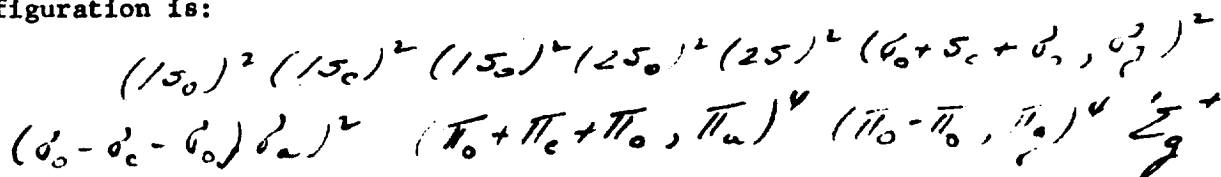


* and many other excited systems.

The electronic energy level diagram is shown in Fig. 1.

II. OBSERVATION OF CO₂ SPECTRA

Even though no total cross section for all these processes is available, information as to their relative importance can be inferred from a number of observations made. This information indicates that the process of exciting CO₂⁺ is favored over disassociation. In literature on classification of CO₂ spectra, it was found that in discharges containing even a small amount of CO₂, a prominent double band progression appeared at 2883-2896 Å. These bands were first attributed to CO₂⁺ by Duffenbach and Smith. Later, Bueso-Sanllehi¹⁷ photographed the spectra under high resolution and classified the lines as belonging to $^2\Sigma^+ \longrightarrow ^2\Pi_g$ of CO₂⁺. The production of these bands agreed with theoretical predictions made by Mulliken²² for CO₂⁺ when a δ_u electron is removed from the neutral atom whose configuration is:



Almost immediately following the work of Buesco Saullehi, Mrosowski,^{18-20,25,26} in a series of five papers, published an extensive analysis of another band system located between 2900-5000 and attributed it to ${}^2\Pi_g - {}^2\Pi_u$ transition of the CO_2^+ molecule. Mrosowski identified 94 sub-bands which he photographed under 350,000 resolving powers and .4A/mm dispersion and finally measured the lines to an accuracy of .001A. (The lower vibrational and rotational levels of CO_2 are shown in Figs. 4, 5).

These same bands were recently observed by Nishimura⁸² who produced them by electron impact. His observations included unresolved $\text{CO}_2^+ {}^2\Pi_u \rightarrow {}^2\Pi_g$ bands using 400 ev electron beam and $\text{CO}_2^+ {}^2\Sigma_u \rightarrow {}^2\Pi_g^+$ using 100-800 ev beam. In his study, Nishimura observed that the CO_2^+ intensities were stronger than those obtained by observation of the produced first Negative system of nitrogen produced by incident electron beams on N_2 . These CO_2^+ bands were also produced using ultraviolet photon excitation by Judge Bloom Morse²⁵ who pointed out that the intensities of CO_2^+ are much stronger than lines observed in the OI, CI, or CO spectra. This indicates that the ionization of CO_2 is preferred over disassociation of the molecule.

These bands appeared in the atmosphere of Venus, and radiation of cometary spectra has been attributed to the same band system. In the laboratory, Poulizas and Dufay⁶⁸ observed the reaction of incident protons on CO_2 to find that ${}^2\Sigma_u$ and ${}^2\Pi_u$ states of CO_2^+ became populated. They noted the absence of any lines belonging to OI and OII spectra, further indicating that the disassociation cross sections of CO_2 are small.

III. CO_2 FRANK-CONDON FACTORS

Approaching the intensity calculations from a theoretical standpoint, Sharp and Rosenstock⁵⁹ give a general technique for calculating Frank-Condon factors in the harmonic oscillator approximation. Their calculation is based on the geometry and vibrational frequencies of the initial and final states. They point out that in going from CO_2 to CO_2^+ , an appreciable bond length change appears, causing a higher population of the $^2\Pi_g$ (ground state of CO_2^+) than of the CO_2^+ excited state $^2\Pi_u$. Subsequently, Brundle and Turner obtained experimental values for Frank-Condon factors and recalculated the Frank-Condon factors using the method of Sharp and Rosenstock with a corrected value for $\sqrt{3}$. They found that good agreement existed between experiment and theory. Their work showed that in addition to (200) vibrational level, the level (002) is equally populated and is in agreement with experimental work done under high resolution by Villarejo.⁶⁹ The Frank-Condon factors obtained by Brundle and Turner⁸⁷ show the relative strength of the (000) level is populated (Fig. 2).

IV. COMPARISON OF CO_2^+ BANDS WITH FIRST NEGATIVE SYSTEM OF N_2

Comparing the fluorescence produced by incident electron beams on CO_2 and N_2 , we note that CO_2 state Π_u (01'0) is 667 cm^{-1} above the ground state and consequently 15% populated, whereas the first excited vibrational state of N_2 is 2360 cm^{-1} and 1% populated. Furthermore, the next excited states of CO_2 (02'0) and (10'0) at 500K are about 2% populated, resulting in minor contributions to the produced fluorescence. These considerations, together with the Frank-Condon factors and the appropriate selection rules,

indicate that only the ground state of CO_2 is contributing to the fluorescence of the ${}^2\Pi_u \longrightarrow {}^2\Pi_g$ system. The rotational structure in N_2 is clear and not superimposed, whereas that of CO_2^+ overlaps various bands. It is evident, examining the strong CO_2^+ transitions, that although the total intensity of the vibrational envelope for CO_2^+ might be larger than the corresponding for N_2^+ , the intensity in CO_2^+ is distributed over more lines and therefore the intensity of an individual rotational component can be considerably weaker. The increased number of lines and their close proximity requires an increase in the resolving power of the observing instrument. This increase is obtained at the expense of speed, thus further decreasing the intensity.

We further note that in the case of CO_2^+ , all lines belonging to the R branch of the transition $(200) {}^2\Pi_{3/2u} \longrightarrow (000) {}^2\Pi_{3/2g}$ with J values varying from 0 to 20 are within $.3 \text{ \AA}$ and that lines belonging to the P branch corresponding to $(200) {}^2\Pi_{3/2u} \longrightarrow (000) {}^2\Pi_{3/2g}$ with J values varying from 26 to 36 are of the same wave length. These features of overlapping spectra would cause the main difficulty in the analysis of the intensities. In comparison to CO_2^+ spectra, we note that in N_2^+ the spacings are relatively large and free of overlap. Consequently, the overlap problem is ignored and larger slits can be used in the experiment to observe an integrated intensity.

V. CONCLUSIONS

The literature search of the feasibility of using electron-excited

CO_2^+ spectra for measuring temperature in a gas indicates that the intensities will be more difficult to analyze than those used in N_2^+ . The technique used will suffer from low intensity and requirements of high resolution. It seems that a Raman spectra recently published on N_2 and CO_2 using a high energy Argon ion laser appears extremely promising in that the rotational lines of the obtained spectra were well resolved.

Special attention is placed on the following literature selections:

- a. Introduction to triatomic spectra
1, 2, 4, 9, 11, 12, 13, 14, 16, 21, 22, 56.
- b. Introduction to classification CO_2^+ spectra
5, 17, 18, 19, 20, 25, 26
- c. The CO_2 ground rotational splitting
10, 23, 34, 38
- d. Measurements and methods of populating CO_2^+
 - i. Electron impact measurements of photoionization
and impact cross section
60, 64, 76, 79, 81
 - ii. Excitation by protons of CO_2^+
68
 - iii. Photoelectron spectroscopy
77, 86
- e. Theoretical treatment of CO_2^+ spectra (Frank-Condon
factors)
59, 80
- f. Absorption, photoionization and fluorescence
27, 35, 53, 55, 63, 69, 84
- g. Raman scattering
78, 87, 88

1. DENNISON D.M.; Phys. Rev., Vol. 28, p. 318-34, (1926)
The Rotation of Molecules
2. KRONIG R.L., RABI I.I.; Phys. Rev., Vol. 29, p. 262-9, (1927)
The Symmetrical Top in the Undulatory Mechanics
3. SMYTH H.D.; Rev. of Modern Phys., Vol. 3, p. 347, (1931)
4. DENNISON D.M.; Rev. Mod. Physics, Vol. 3, p. 280-335, (1931)
The Infrared Spectra of Polyatomic Molecules, Part I
5. SMYTH H.D.; Phys. Rev., Vol. 38, p. 2000-15, (1931)
The Emission Spectra of Carbon Dioxide
6. SMYTH H.D.; Phys. Rev., Vol. 39, p. 380-2, (1932)
The Spectrum of Carbon Dioxide. II. Electron Levels
7. SCHMID R.F.; Phys. Rev., Vol. 41, p. 732-50, (1932)
Rotational Analysis of some CO₂ Emission Bands. Part I.
8. MULLIKEN R.S.; Phys. Rev., Vol. 42, p. 364-72, (1932)
On The Interpretation of the Rotational Structure of the CO₂ Emission Bands
9. MULLIKEN R.S.; Phys. Rev., Vol. 40, p. 55-62, (1932)
Electronic Structures of Polyatomic Molecules and Valence
10. MARTIN P.E., BARKER E.F.; Phys. Rev., Vol. 41, p. 291-6, (1932)
The Infrared Absorption Spectrum of Carbon Dioxide
11. DENNISON D.M.; Phys. Rev., Vol. 41, p. 304-12, (1932)
The Vibrational Levels of Linear Symmetrical Triatomic Molecules
12. MULLIKEN R.S.; Phys. Rev., Vol. 43, p. 279-302, (1933)
Electronic Structure of Polyatomic Molecules and Valence. IV.
Electronic States, Quantum Theory of a Double Band
13. ADEL A., DENNISON D.M.; Phys. Rev., Vol. 44, p. 99-104, (1933)
The Infrared Spectrum of Carbon Dioxide, Part II.
14. MULLIKEN R.S.; Jour. Chem. Phys., Vol. 3, p. 720-39, (1935)
XIV. Linear Triatomic Molecules, Especially Carbon Dioxide
15. PRICE W.C.; SIMPSON D.M.; Proc. Roy. Soc. A, Vol. 169, p. 501-12, (1939)
The Absorption Spectra of Carbon Dioxide and Carbon Oxy sulfide in the Vacuum
Ultra Violet
16. DENNISON D.M.; Reviews of Mod. Physics, Vol. 12, No. 3, p. 175-8, (1940)
The Infrared Spectra of Polyatomic Molecules. Part II
17. BUESCO - SANLLEHI F.; Phys. Rev., Vol. 60, p. 556-70, (1941)
Rotational Analysis of the 2900 Å Band of CO₂⁺

18. MROZOWSKI S.; Phys. Rev., Vol. 60, p. 730-8, (1941)
On the $2\pi_u \rightarrow 2\pi_g$ Bands of CO_2^+ . Part I
19. MROZOWSKI S.; Rev. of Mod. Physics, Vol. 14, p. 216-8, (1942)
Emission Spectrum of the Ion CO_2^+
20. MROZOWSKI S.; Phys. Rev., Vol. 62, p. 270-9, (1942)
On the $2\pi_u \rightarrow 2\pi_g$ Bands of CO_2^+ . Part II
21. BARKER E.F.; Rev. Mod. Phys., Vol. 14, p. 198-203, (1942)
VII. Spectra of Simple Molecules; The Infra Red Spectra of Triatomic Molecules
22. MULLIKEN R.S.; Rev. Mod. Phys., Vol. 14, p. 204-15, (1942)
Electronic Structures and Spectra of Triatomic Oxide Molecules
23. NIELSEN A.H., YAO Y.T.; Phys. Rev., Vol. 68, No. 7 and 8, p. 173-80, (1945)
The Analysis of the Vibration-Rotation Band CO_3 for $\text{C}^{12}\text{O}^{16}_2$ and $\text{C}^{13}\text{O}^{16}_2$
24. NIELSEN A.H., YAO Y.T.; Phys. Rev., Vol. 71, No. 11, p. 825 (1947)
Rotation B and W_3 for $\text{C}^{12}\text{O}^{16}_2$ and $\text{C}^{13}\text{O}^{16}_2$.
25. MROZOWSKI S.; Phys. Rev., Vol. 72, No. 8, p. 682-90, (1947)
On the $2\pi_u \rightarrow 2\pi_g$ Bands of CO_2^+ Part III
26. MROZOWSKI S.; Phys. Rev., Vol. 72, No. 8, p. 691-8, (1947)
On the $2\pi_u \rightarrow 2\pi_g$ Bands of CO_2^+ . Part IV
27. WILKINSON P.G.; JOHNSTON H.L.; Jour. Chem. Phys., Vol. 18, No. 2, p. 190-3
The Absorption Spectra of Methane, CO_2 in the Vacuum Ultra Violet
28. GOLDBERG L. and oth.; Phys. Rev., Vol. 76, No. 12, p. 1848-58, (1949)
Carbon Dioxide in the Infrared Solar Spectrum
29. KAPLAN L.; Jour. Chem. Phys., Vol. 18, No. 2, p. 186-9, (1950)
Line Intensities and Absorption for the 15 Microns CO_2 Band
30. EGGERS D. F. JR., CRAWFORD B.L.; Jour. Chem. Phys., Vol. 19, No. 12, p. 1454-61 (1951)
Vibrational Intensities. III. Carbon Dioxide and Nitrous Oxide
31. GAILAR N.N., PLYER E.K.; Jour. Res. Nat. Bur. Stand., Vol. 48, No. 5, p. 392-394, (1952).
The 3 Bands of Carbon Disulfide and Carbon Dioxide
32. DE HEER J., NILSEN H.H.; Jour. Chem. Phys., Vol. 20, No. 1, p. 101-4, (1952)
1 type doubling in Energy Levels of Carbon Dioxide Coupled by Fermi Resonance
33. PLYLER E.K., BALL J.J.; Letters to the Editor, p. 1178-9, (1952)
The Infra Red Emission Spectra of OH, CO, and CO_2 from 3 micron to 5.5 micron
34. HERZBERG G., HERZBERG L.; Journ. Opt. Soc. America, Vol. 43, No. 11, p. 1037-44, (1953).
Rotation-Vibration Spectra of Diatomic and Polyatomic Molecules with Long Absorbing Paths XI. Spectrum of CO_2 below 1.25 micron.
35. WATANABE K., INN E.C., ZELIKOFF; Jour. Chem. Phys., Vol. 21, No. 10, p. 1648-53, (1953).
Absorption Coefficients of Gases in the Vacuum Ultraviolet. Part III- CO_2

36. MORRISON J.D.; Chem. Phys., Vol. 22, No. 7, p. 1219-23, (1954)
Studies of Ionization Efficiency. Part IV. The Electron Spectra of Simple Molecules.
37. PLYER E.K. and oth.; Jour. Res. Nat. Bur. Stds., Vol. 55, No. 4, p. 183-9, (1955)
Infrared Absorption and Emission Spectra of Carbon Monoxide in the Region from 4 to 6 Microns
38. FRANCE W.L., DICKEY F.P.; Jour. Chem. Phys., Vol. 23, No. 3, p. 171-4, (1955)
Fine Structure of the 2.7 Micron Carbon Dioxide Rotation-Vibration Band.
39. COURTOY C.P., HERZBERG G.; Jour. Chem. Phys., Vol. 23, p. 975-6, (1955)
Effect of Fermi Resonance on the Centrifugal Stretching Constant in CO₂
40. AMAT G., GOLDSMITH M. T.; Jour. Chem. Phys., Vol. 23, p. 1171-2, (1955)
Theory of the Taylor-Benedict - Strong Effect
41. HAMILTON W.C.; Letters to the Editor, p. 1283, (1956)
Quadrupole Moments of CO₂
42. BODI L., CURTIS C.F.; Jour. Chem. Phys., Vol. 25, No. 6, p. 1117-22, (1956)
Theory of Potational-Vibrational Interaction in Polyatomic Molecules
43. ROSSMANN K., FRANCE W., NARAHARI K.; Jour. Chem. Phys., Vol. 24, No. 6, p. 1007-8, (1956).
Infra Red Spectrum and Molecular Constant of CO₂; levels 10⁰⁰ and 02⁰⁰, 10⁰¹ and 02⁰¹ coupled by Fermi Resonance
44. COURTOY P.C.; Canad. Jour. of Phys., Vol. 35, No. 5, p. 608-48, (1957)
The C¹²O¹⁶ Spectrum between 3500 and 8000 cm⁻¹ and Molecular Constants of This Molecule
45. KAPLAN L., KOSTOWSKI H.J.; Jour. Chem. Phys., Vol. 26, No. 5, p. 1252-53, (1957)
Absolute Intensities of the 721 and 742 cm⁻¹ Bands of CO₂
46. COHEN D., LOWE R., HAMPSON J.; Jour. App. Phys., Vol. 28, No. 6, p. 737-41, (1957)
Infrared Emission from High Frequency Discharges in CO₂
47. TAYLOR J., BENEDICT W., STRONG J.; Jour. Chem. Phys., Vol. 20, No. 12, p. 1884-98, (1957) - Infrared Spectra of H₂O and CO₂ at 500° C.
48. KOTOV Y., TYULIN V., TATEVSKI V.; Optika: Spektroskopija, Vol. 4, No. 2, p. 271-2, (1958) (In Russian)
49. STOICHEFF B.P.; Can. Journ. of Phys., Vol. 36, No. 2, p.-218-30, Feb. (1958)
High Resolution Raman Spectroscopy of Gases, XI. Spectra of CS₂ and CO₂
50. TANAKA Y., JURSA A.S., LEBLANC F.J.; Jour. Chem. Phys., Vol. 28, p. 350-1, (1958)
Higher Ionization Potentials of Linear Triatomic Molecules CO₂ and ...
51. OVEREND J., and oth.; Jour. Chem. Phys., Vol. 38, No. 2, p. 532-7, (1958).
Vibrational Intensities, XI. CO₂ and Wilson-Wells Method.
52. WENTINK T.; Jour. Chem. Phys., Vol. 30, No. 1, p. 105-15, (1959)
Triatomic Linear Molecules Containing Carbon and Oxygen, Sulfur, Selenium or Tellurium. II. Potential Constants.

53. TANAKA Y., JURSA S., LEBLANC F.J.; Jour. Chem. Phys., Vol. 32, No. 4, p. 1199-205, (1960). Higher Ionization Potentials of Linear Triatomic Molecules-I.CO₂
54. PLASS G.N.; Jour. of Opt. Soc. Amer., Vol. 49, No. 8, p. 821-8, (1959) Spectral Emissivity of Carbon Dioxide from 1800-2500 cm⁻¹
55. TANAKA Y., OGAWA M.; Canad. Jour. of Physics, Vol. 40, p. 879-86, (1962), Rydberg Absorption Series of CO₂ Converging to the ² u State of CO₂
56. HERZBERG G.; Trans. of Faraday Soc., No. 35, p. 7-28, (1963) Determination of the Structures of Simple Polyatomic Molecules and Radicals in Electronically Excited States
57. KAPLAN L.D., MUNCH G., SPINRAD H.; Astrophys. Journ., Vol. 139, No. 1, p. 1-15, (1964). An Analysis of the Spectrum of Mars
58. JOHNS J.W.C.; Canad. Jour. of Phys., Vol. 42, p. 1004-7, (1964) A New Assignment of Some CO₂⁺ Bands
59. SHARP T.E., ROSENSTOCK H.M.; Jour. Chem. Phys., Vol. 41, No. 11, p. 3453-3463, (1964), Franck-Condon Factors for Polyatomic Molecules
60. RAPP D., ENGLANDER P.; Jour. Chem. Phys., Vol. 43, No. 5, p. 1464-75, (1965). Total Cross Sections for Ionization and Attachment in Gases by Electron Impact
61. FARRENQ R., ROSSETTI and oth.; C. R. Acad. Sc. Paris, Vol. 263, Ser. B, p. 241-3, (1966). Study of the CO₂ Band at 1064 cm⁻¹ (in French)
62. STATZ H., TANG C.L., KOSTER G.F.; Jour. Appl. Phys., Vol. 37, No. 11, p. 4278-84, (1966). Transition Probabilities between Laser States in Carbon Dioxide
63. COOK C.R.; METZGER P.H., OGAWA M.; Jour. Chem. Phys., Vol. 44, No. 8, p. 2935-42, (1966). Absorption, Photoionization and Fluorescence of CO₂
64. NISHIMURA H.; Jour. of Phys. Soc. Japan, Vol. 21, p. 564-5, (1966) Measurements of the Excitation Function of CO₂⁺ by Electron Impact
65. KORYAZHKIN V.A.; Soviet Physics Doklady, Vol. 11, No. 4, p. 329-31, (1966). Geometry of CO₂⁺ and the Energy Levels of Slightly Asymmetrical Top Triatomic Molecules in ² Degenerate States
66. SJOGREN H.; Arkin for Fysik, Band 32, 30, p. 529-34, (1966) Formation of Carbon Dioxide Ions After Electron and Ion Impact

67. GRAY L.D.; Jour. Quant. Spectrosc. Radiat. Transfer, Vol. 7, p. 795-803, (1967). Relative Intensity Calculations for Carbon Dioxide -III. Relative Line Intensities of Transitions from the Vibrational Ground State for Temperatures from 160° to 280° K.
68. POULIZAC M.C., DUFAY M.; Physical Letters, Vol. I, p. 17-20, (1967) Evaluation of $\text{CO}_2^+ 2u 2g$ Vibrational Transition Probabilities
69. VILLAREJO D., STOCBAUER R., INGRAM M.G.; J. Chem. Phys., Vol. 48, (Letters to the Editor), p. 3342-3, (1967) Photoionization of CO_2 , and the Franck-Condon Principle for Polyatomic Molecules
70. FREUND R.S., KLEMPERER W.; Jour. Chem. Phys., Vol. 47, No. 8, p. 2897-904, (1967). Molecular Beam Time of Flight Measurements for the Study of Metastable and Repulsive Electronic States
71. ORTENBERG F.S., ANTROPOV E.T.; Soviet Physics Uspekhi, Vol. 9, No. 5, p. 717-42, (1967). Probability of Electron-Vibrational Transitions in Diatomic Molecules
72. CARNEVALE E.H., CAREY C.; Jour. Chem. Phys., Vol. 47, No. 8, p. 2529-35, (1967). Ultrasonic Determination of Rotational Collision Numbers and Vibrational Relaxation Times of Polyatomic Gases at High Temperatures
73. TICE R., KIVELSON D.; Jour. Chem. Phys., Vol. 46, No. 12, p. 4248-54, (1967). Cyclotron Resonance in Gases. II. Cross Sections for Dipolar Gases and for CO_2
74. MC CUBBIN T.K.; Jour. Opt. Soc. Amer., Vol. 57, No. 11, p. 1373-5, (1967) Infrared Emission of $\text{CO}_2\text{-N}_2$ and $\text{CO}_2\text{-N}_2\text{-He}$ Plasmas
75. ECHIGO R., NISHIWAKI N.; Bull. JSME, Japan, Vol. 10, p. 671-9, (1967) Evaluation of Band Emissivities of CO_2 and Water Vapor
76. CARETTE J.D.; Canad. Jour. Phys., Vol. 45, p. 2931-38, (1967) The Ionization of CO_2 and N_2O by Electron Impact (trans. from French)
77. TURNER D.W., MAY D.P.; Jour. Chem. Phys., Vol. 46, No. 3, p. 1156-60, (1967). Franck-Condon Factors in Ionization: Experimental Measurements Using Molecular Photoelectron Spectroscopy IX II.
78. BARRETT J.J., ADAMS N.I. III; J. Opt. Soc. Am., Vol. 58, p. 311-319, March 1968. Laser-Excited Rotational-Vibrational Raman Scattering in Ultra-Small Samples
79. BONESS M.J., SHULZ G.J.; Phys. Rev. Letters, Vol. 21, No. 15, p. 1031-4, (1968). Vibrational Excitations of CO_2 by Electron Impact
80. CONKEY M.C. and oth.; J. Phys. B. (Proc. Phys. Soc.) 1968, Ser. 2, Vol. I (GB). Absolute Cross Sections for Ionization and Excitation of CO_2 by Electron Impact

81. PETROPOULOS B.; C. R. Acad. Sc. Paris, Vol. 226, Series B, p. 276-8, (1968). Quantitative Study of $2\pi_u \rightarrow 2\pi_g$ of CO_2^+
82. NISHIMURA H.; Jour. Phys. Soc. Japan, Vol. 24, No. 1, p. 130-42, (1968). Excitation of N_2^+ , O_2^+ and CO_2^+ Band by Electron Impact
83. CUTHEERT J.F. and oth.; J. Phys. B. (Proc. Phys. Soc.), 1968, Ser. 2, Vol. 1, p. 62-70 (GB). Sequential Mass Spectroscopy III. Ions and Fragments from CO_2
84. PETROPULOS B., BOTTER R.C.R.; Acad. Sc. Paris, t. 266, Series B, p. 404-7, (1968). Franck-Condon Factors for Ionization of CO_2 (translated from French)
85. JUDGE D.L., BLOOM G.S., MORSE A.L.; Canad. Jour. of Physics, Vol. 47, p. 489-97, (1969). Studies of CO_2^+ [$R^2\pi_u \rightarrow 2\pi_g$] Bands Using Photon Excitation From the Neutral Molecule
86. GARDNER P.J., KASHA M.; Jour. of Chem. Phys., Vol. 50, No. 4, p. 1543-52, (1969). Electronic Consequences of Vibrational Defficiency in Polyatomic Molecules
87. BRUNDLE C.R., TURNER D.W.; Jour. Mass. Spectr. and Ion Phys. Amsterdam, Vol. 2, p. 195-220, (1969). Studies on the Photoionization of the Linear Triatomic Molecules N_2O , COS , CS_2 and CO_2 Using High Resolution Photoelectron Spectroscopy
88. PEUNEY C.M.; J. Opt. Soc. Am., Vol. 59, p. 34-42, Jan. 1969
Light Scattering in Terms of Iscillator Strengths and Refractive Index
89. BARRETT J.J., WEBER A.; J. Opt. Soc. Am., Vol. 60, p. 70-77. January 1970.
Pure-Rotational Raman Scattering in a CO_2 Electric Discharge.

$\cdot 10^3$
 cm^{-1}

CO_2^+

$\tilde{C}^2\Sigma_g^+$

$\tilde{B}^2\Sigma_u^+$

$\tilde{A}^2\Pi_u$

$\tilde{X}^2\Pi_g$

150

100

50

ELECTRONIC STATES OF CO_2

$\tilde{X}'\Sigma_g^+$

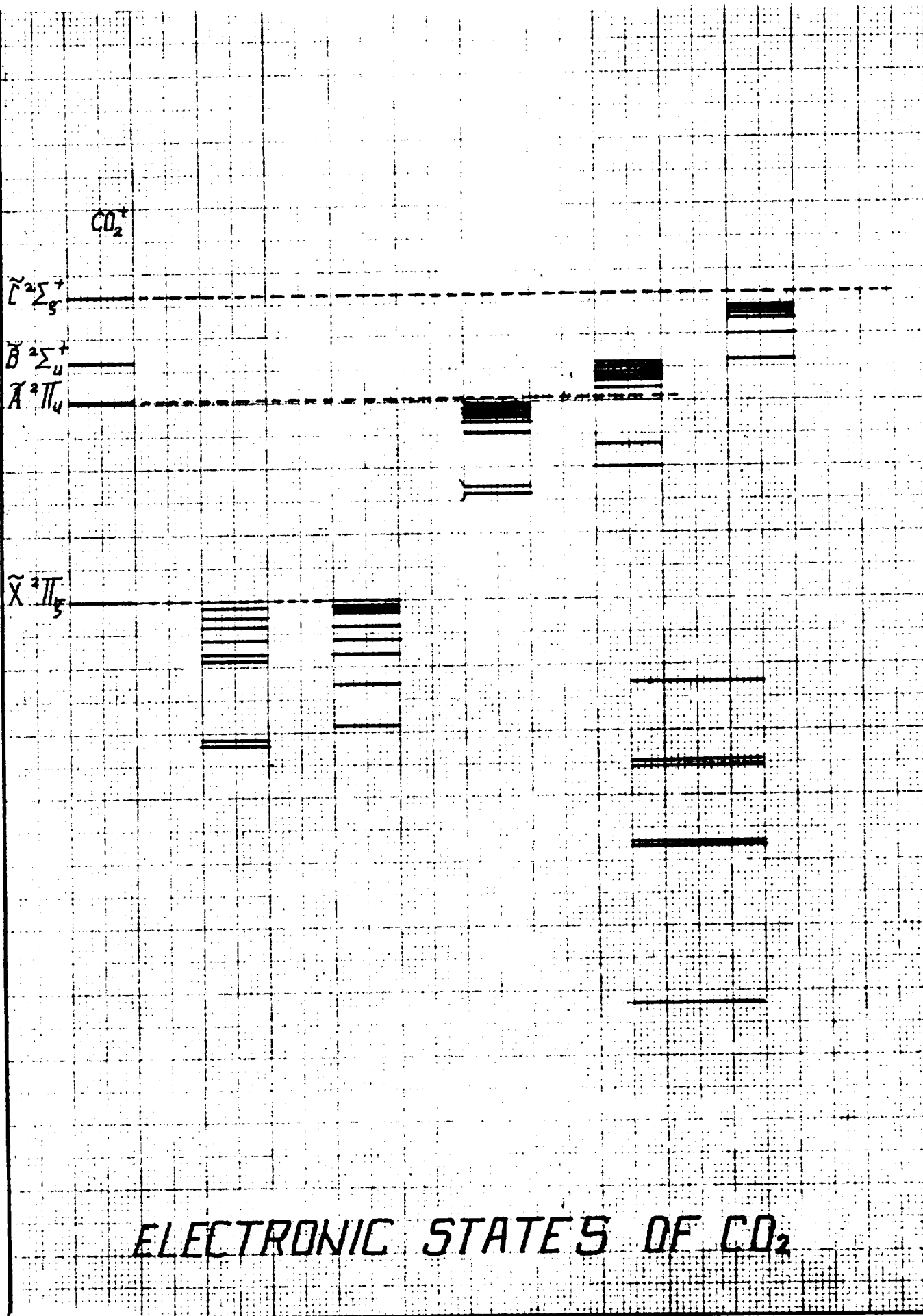
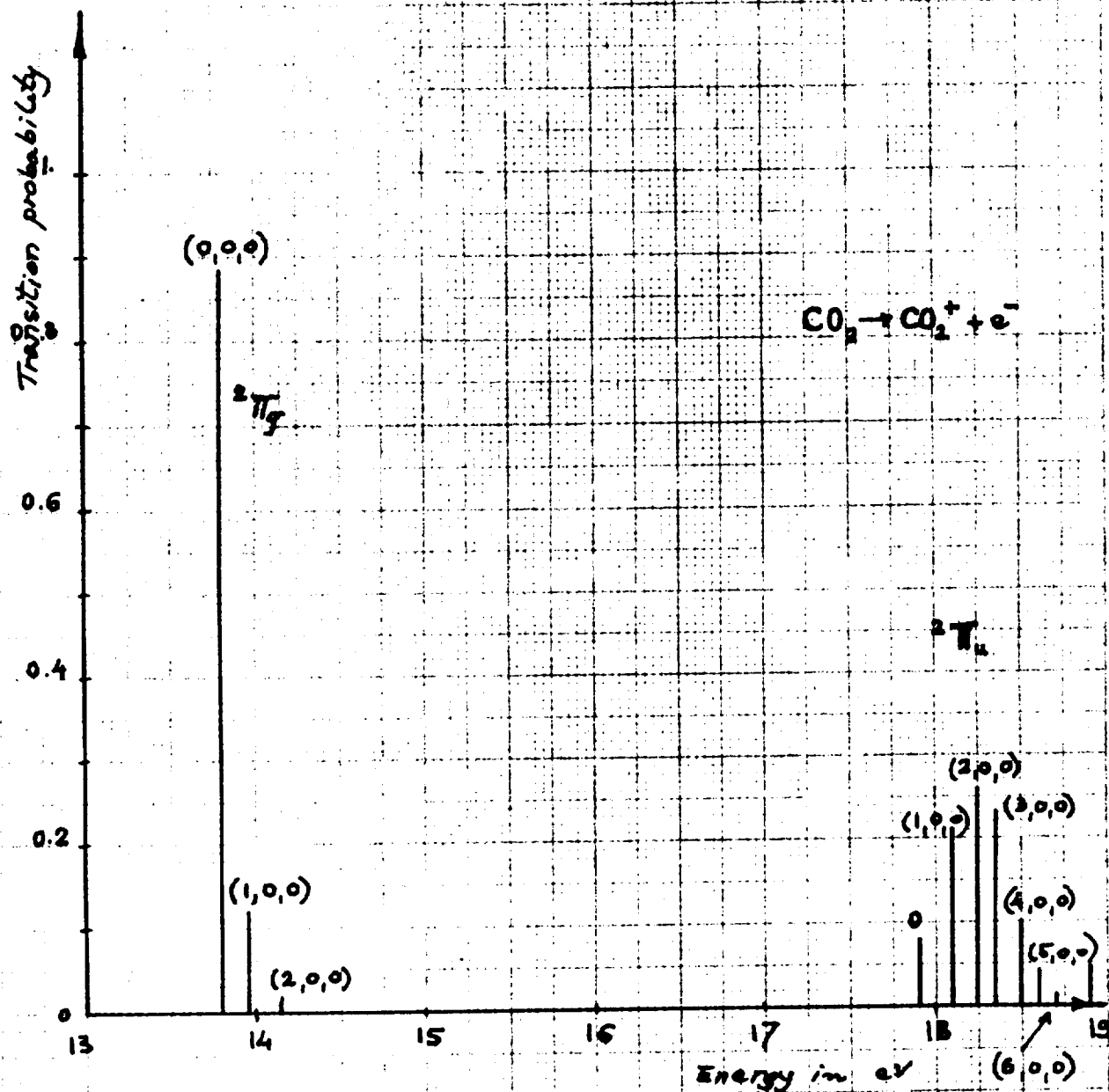
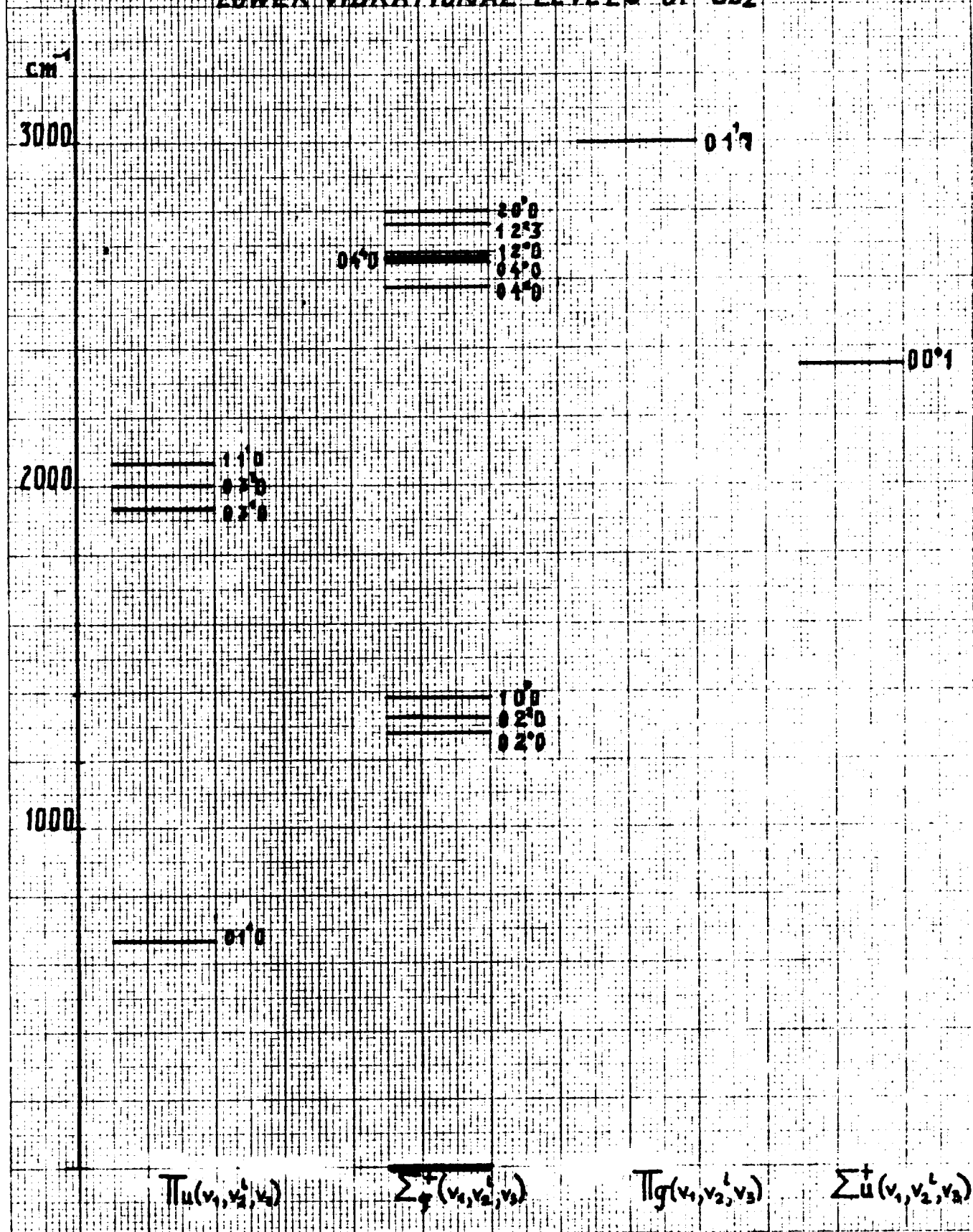


Figure 2



Transition probabilities calculated for CO_2 ion (two states)
 The total transition probability to each state is normalized to 1

LOWER VIBRATIONAL LEVELS OF CO₂

10^3 cm^{-1}

38

36

34

32

30

28



14

12

10

8

6

4

2

0

$2\pi_{1/2 u}$

$2\pi_{1/2 g}$

7

6

5

4

3

2

1

0

$\text{CO}_2^+ \quad 2\Sigma^+$

$2\pi_{3/2 u}$

$2\pi_{3/2 g}$

8

7

6

5

4

3

2

1

0

LOWER VIBRATIONAL LEVELS OF CO_2^+

Vibrational and Rotational Structure of π bands of CO_2^+

3
10 cm⁻¹

34

33

32

31

30

29

28

10

9

8

7

6

5

4

3

2

1

0

20 Squares to the Inch

$2\pi_{3/2}^0$

$2\pi_{1/2}^0$

